Field-Assisted DC-Pulsed Cathodes for next generation light sources and accelerators

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FIELD-ASSISTED DC-PULSED CATHODES
For next generation light sources and accelerators

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Summary

Electron beam luminosity and ultra low emittance are today very important parameters for futur light sources and colliders. In a Free Electron Laser, [2] for good performances, the normalized beam emittance is given by $\epsilon = \frac{\beta}{L_g}\frac{\lambda\gamma}{4\pi}$, whith λ the optical wavelength, γ the energy of the beam, β the β function and L_g the gain length. It is then possible to reduce the energy of the beam and the length of the Linac, (β parameter), provided ϵ is sufficiently low. For colliders, [5] let's take Higgs cross section 50fbarn, so with a luminosity of 10^{34} we can hope $N_{event/s} = 510^{-4}$. As we have $\mathcal{L} \sim \frac{I_1 I_2}{\epsilon_1\epsilon_2}$, we see here that goals of luminosity and emittance do not always coincide; the extraction charge may distinguish the two. Our project $ABRICo_{231}$ -ie Acceleration BRIllante et Compacte- is devoted to a medium to low electronic beam charges, in the range 1 to 50 pC, with hope to investigate ultra low charges for some other researches [a]. Clearly we favor beam emittance $\epsilon < 1mmmrad$.

We intend to make an experiment, based on DC-pulsed sub nanosecond nanostructured (photo)-cathode [b], in field assisted emission regime; for the moment we are implied in the development of a nanosecond HV pulsed source which will be used in the system.

These objectives necessitate a careful design. Particularly, even if the transverse dimension of the emitters is tiny (some 50nm) their transverse momentum is not. The radiated defocusing electromagnetic field and space charge are responsible of the degradation of the emittance due to transverse momentum.

In order to better understand the electromagnetic effects on nanostrutures, we discuss the pertinence of a modelling based on curvilinear coordinates Maxwell solving (C-method)[6].

a. high charges however, could be reached by high repetition frequencies
b. the photoemission technique is not mandatory, but for the moment it is the only way to generate short bunches

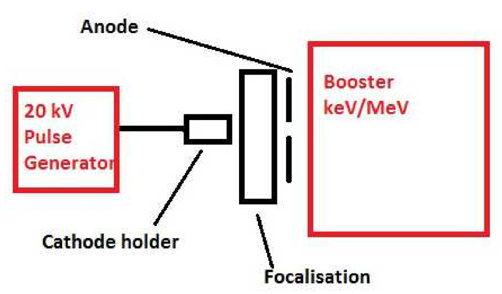
I Low emittance keV source

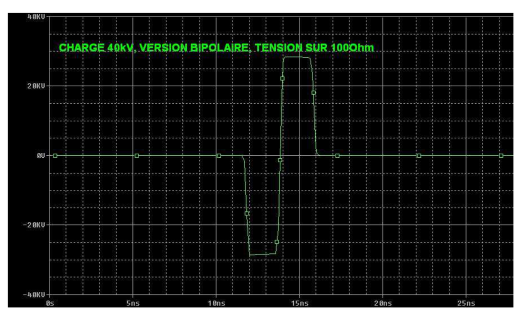
1. The keV source

Field effet is a drawback for good emittance of electron guns. But if we use the field effect as an emission technique, specially in very short pulses, the advantages are the followings :

1. **high quality polishing cathodic surface is no longer necessary,**
2. **for short pulses, the breakdown level is raised above Kilpatrick limits**. In fact, for nanosecond pulses, the augmentation is targeted to 40%. That level is probably higher for subnanosecond pulses.

We have defined our source as the following diagram :



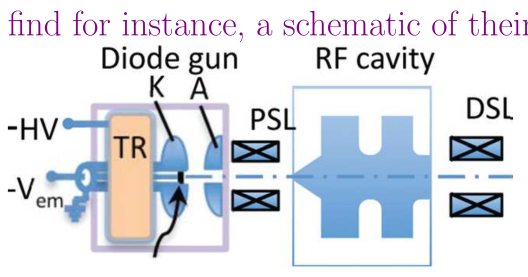


Schema of the system — Output of the 20kV generator (on 10Ω)

The generator is a 20kV peak High Pulsed Power, HPP, adapted to 100Ω. The planned waveform is represented above and is applied between a cathode fixed on a cathode holder, and an anode. The whole chamber is immersed in a medium vacuum (10^{-6} to $10^{-8} Torr$).
Immediately after the iris, the keV bunch is to be accelerated to MeV range by a compact design, for example a Dielectric accelerator. The source is made in state of art techniques, but her realization and tuning are not trivial. We designed the wave former according a description given in [7], but numerous improvments have been added.
Several electromagnetic simulations were made and permitted us to accurately define the internal details of the waveformer. All the drawings have been reported into software mechanical @Catia project. The entire HPP source should be construct inside that trimester.

2. Nanostructured cathodes,PSI experiments

The Paul Sherrer Institute, PSI,([10]) has explored since several years the possibility of field emission for electron sources. The strength of their work lays upon designing new nanostructured Field Emission Array, FEA's. We find for instance, a schematic of their power source in the figure hereafter :



We notice the RF Cavity, driving the beam to MeV range. **With an exclusively electric trigger**, they obtained a 400ps FWHM bunch, but the emittance raised from the value of 0.1mmmrad to 1mmmrad at MeV range, the performances of a good RF gun with polished cathode. **The major issues in field emission domain stay inside :**

1. **the nature and electromagnetic coupling of nanostructured cathodes,**
2. **the emittance degradation of transport from keV to MeV.** [a]

a. In addition, we report ([9]) that heating of tips -when we use them- may be a nanosecond process.

II Design of the accelerating cell

1.Capacitive against pseudo resonant injection

We have noticed that nanosecond pulses should yet be too long to permit a convenient transport from cathode to anode. **There are two scenarios :**

1. **injection in a non resonant space, so the gap cathode anode is seen as prominently capacitive,**
2. **injection in a pseudo-resonant space, with low quality coefficient, so high bandwidth.**

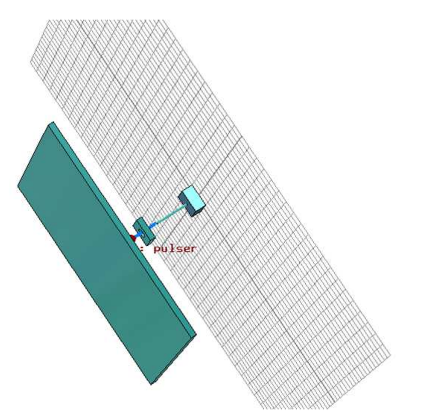
In the first cas, our simulations show that above $C_{cathodeanode} \gtrsim 10pF$, which is difficult to reach with low distances, the rise times will be distorted. In the second cas, we noticed that the transition times of the waveform are of the same range that the plateau. Hence, the real output will be constitued in major part by its fundamental frequency. If we design the cathode-anode gap as being pseudo-resonant, we can take in account the first Bessel TM01 mode with the well-known frequency $f_{TM01} = \frac{c*2.4}{2*\pi*a}$ where a is the radius of the cell, c the speed of light. With such a bipolar waveform, we excite that first mode for $a = 68cm$, which is far too large. We see two directions to solve that issue : next generation or evolution of our pulsed source could be in the range 100ps or less. It opens the way to **ultra-fast HPP sources**. In other side, the field-assisted photoemission technique permits to free us from acceleration of the entire bunch.

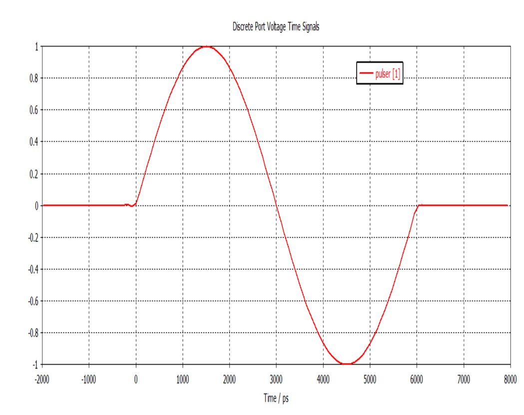
2.Simulations of simple systems

2 cases to investigate :

1. **field emission without photoemission,**
2. **transport of the bunch with photoemission.**

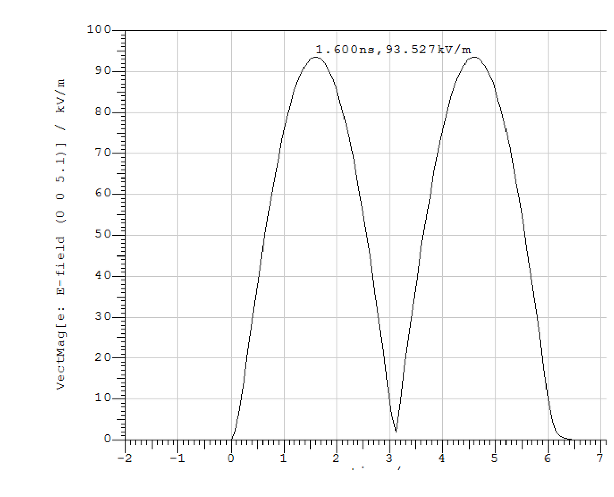
The configuration 'tip-plane' is elementary. If the beam is not focused, all the electric lines are orthogonal to the apex of the tips, so their divergence is high. Several setups are conceivable to remedy to it. We try here, with CST studio, the triode configuration as [10]. It is represented by the figure hereafter





triode configuration — bipolar signal

The waveform is also reported, normalized to 1Volt. The dimensions are for the cathode, $2\times2\times1$, for the anode, $20\times20\times0.5$, for the gate $2\times2\times0.5$, for the tip a cylinder of radius 0.1 and length 3, and for the apex, an hemisphere at the end of the tube. There is no unity : I firstly tried μm realistic units, regarding [10]. But the computation time was excessive, so I raised progressively the dimensions to non realistic ones. The computation time became accessible when dimensions reached mm. the pulser signal is -intentionally-taken sinusoidal at 166MHz, then the corresponding wavelength is $1.8m$



Whatever any time electromagnetic method, TLM, FDTD,... The Current condition imposes the mesh dimensions to be such that $\Delta L > c\Delta t$. For a nanometric range, say 50nm, the mesh is probably a under multiple of that, say 5nm. Hence $\Delta t = \frac{510^{-9}}{310^8}$ then $\Delta t \sim 1.510^{-17}s$, so the number of iterations are approximately $N_{max} = \frac{610^{-9}}{1510^{-17}} \sim 410^7$; but at each step, there are also matrix recalculation for instance... The frequency range has an influence on the time taken for matrix calculations, but far less important. In the figure above, we represent the absolute value of electric field for 1V signal at a $100\mu m$ of the apex surface. The high peak value could be a numerical artifact, but the waveform is realistic.

Références

[1] Chen Yu-Juian & Al. Beam transport in a dielectric wall accelerator for intensity modulated proton therapy. *Proceeding of IPAC2011, San Sebastiàn, Spain*, 2011.

[2] Ganter R & Al. Ultra low emittance gun project based on field emission. *Proceeding of Linac2004, FEL conference*, 2004.

[3] Jean-Luc babigeon. Particle accelerators, control and optimization problem for power sources. ., 2014.

[4] Roger & Al Bach. Double slit controled diffraction. *Arxiv, Quantum physics*, october 2012.

[5] Adli Eric. An introduction to particle accelerators, 2014.

[6] Gérard Granet. *Grating theory and numeric applications*. Presses universitaires de Provence, 2012.

[7] Benoit Martin. *Etude et conception d'un étage de mise en forme d'impulsions ultra large-bande de forte puissance*. PhD thesis, Université de Limoges, october 2008.

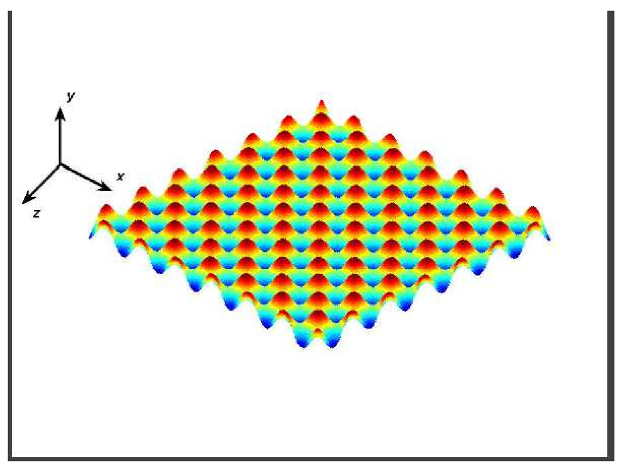
[8] & Al Pozzi R. An experiment on electron interference. *American Journal of Physics 41, 639*, 1973.

[9] Benjamin& Al Seznec. Nanosecond pulses overtake the vacuum de-breakdown voltage and current. ., 2015. to be published.

[10] & Al Tsujino S. Subnanosecond switching and acceleration to relativistic energies of field emission electron bunches from metallic nanotips. *Physics of plasmas, 18, 064502*, 2011.

III Electromagnetic coupling on FEA's

We shall use 2D periodic arrays. However, there are infinite degrees of Freedom in the shape of emitters [a] : prominent cones, holes, truncated cones, tips, spheres,...And on their dispositions. The principal objective is to enhance the quantum yield invoking a possible plasmon polariton coupling in order to reduce the necessary laser power in one photon mode. Techniques used in solar cell, essentially grooves instead of tips, are to investigate.
the semi-analytical C-method is one of the theories which fits optimally to the problem. All the Maxwell equations are treated in the coordinate system which conforms the nanostructural surface. To summarize, C-method is said to be 'a curvilinear coordinate modal method by Fourier expansion'.



More precisely if we consider an orthonormal triedra as on the figure ,the 2D-corrugations may be described ([6]) by a 2 variables function, and one have $z' = a(x,y), x' = x, y' = y$ in the new curvilinear coordinate system. With a covariant form, and expressed in frequency domain, the Maxwell equations are explicited under the system :

$$\xi^{\alpha\beta\gamma}\frac{\partial}{\partial\alpha}\mathcal{F}_\gamma = k\sqrt{g}g^{\alpha\beta}\mathcal{G}_\alpha$$
$$\xi^{\alpha\beta\gamma}\frac{\partial}{\partial\alpha}\mathcal{G}_\gamma = k\sqrt{g}g^{\alpha\beta}\mathcal{F}_\alpha$$
$$\mathcal{F}_\alpha = E_\alpha \qquad \mathcal{G}_\alpha = -jZH_\alpha$$
$$k = \omega\sqrt{\mu\epsilon} \qquad Z = \sqrt{(\frac{\mu}{\epsilon})} \qquad j^2 = -1$$

where E and H are electromagnetic fields, Z the wave impedance of the medium, g the metric of the curvilinear system. We see that Maxwell equations may be established on a corrugated surface, with the help of metric g, whatever the surface. For us **it may constitute a great advantage**, especially due to the tiny dimensions of gratings represented by our FEA's. We have seen precedently that most of solvers generate very long computation times. The next step is to derive the solutions of Helmotz equation $(\delta_x^2 + \delta_y^2 + k^2)\mathcal{F} = \gamma^2\mathcal{F}$ for the propagation of one of the precedent components, ie these modal solutions, invariant by the coordinate change, are in first in Flocquet form, regarding the 1D or 2D periodicity, and the components obtained, are finally expanded in Rayleigh serie. In a change of coordinates, the developpements are similar, but with introduction of the generalized Rayleigh wave expansion. The coefficients of that expansion take account of the surface profile, which is periodic, then developable in Fourier serie.

Discussion :

1. the theory is probably easily generalizable to 2D periodicity. As a cut and try, let's inject the following expression deduced from 1D formulas :

$$\mathcal{F}^+(x_1, x_2, x_3 = z - a(x,y)) =$$
$$\sum_u A^q exp(j\gamma_u x_3) \sum_{vw} exp(j\gamma_u(b(x_1)x_1 + c(x_2)x_2)) exp(j(\alpha_v * x_1 + \beta_w * x_2)$$

$$a(M) = a(M_0 + ue_1 + ve_2) \tag{1}$$

a(M) has 2D periodicity along vector basis $e_1 \& e_2$. Here $\mathcal{F}^+$ is the forward component of $\mathcal{F}$ in Raleigh decomposition, and we postulate that $a(x,y) = b(x) \times c(y)$ which is presumptuous, even if suggested by Helmotz equation.

2. apart the precedent issue, the finite dimensions of the cathode induce some precautions regarding application of Fourier series. We must test a windowing procedure or apply a Fourier transform with complexity consequences, and verify that the results are not distorted. It seems to have the same importance than the Fourier troncature of infinite serie.

3. the central problem is to find the optimal individual structure and collective arrangement of nano emitters, such that their contributions in all of the finite surface will be resonant. It is analog to an optimization problem in filtering technique for instance, ie ' to find the best filter topology which realizes a given tranfer function' [3]

4. 2D arrays could lead to laser depolarization problems in some configurations, as only the 1D case leads to a clear situation ([6])

a. inside the fabrication constraints

IV Prospective

1 Regarding technology point, a challenge of $ABRICo_{231}$ is to realize compacity together with performances and low costs. We also intend to use a travelling wave acceleration and to lay on further THz techniques or dielectric accelerators. These directions make the whole engineering new. For example, beam dynamics are only recently studied inside a dieclectric accelerator. [1]

2 we have examined the possibilities of coding the electromagnetic coupling on FEA's, in the two scenarios of field emission alone, and field-assisted photoemission. It depends critically of the geometry of emitters, and the fabrication constraints, and is -one of next- steps of our work.

3 The ability to generate- but above all to measure it- ultra low charge $\ll 1 FemtoCoulomb$, should opens the door to some fundamental physics experiments ([8],[4]) and also tries to catalogue the engineering consequences in possible accelerator optics. Also Attosecond bunches are to be considered, if we can solve some RF issue, like time propagation on the surface of the cathode

Currently PhD work under the collaborations of Laboratoire du Génie Electrique de Paris (LGEP, Orsay, France), Laboratoire of Accélérateur linéaire (Lal, Orsay), Laboratoire de Physique des Gaz et Plasmas (LPGP Orsay)